Highlights on neutral K decays

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(KLOE collaboration)

Outline

- **Recent experimental inputs for CPT and the unitarity relation:**

1. $\mathbf{a}_{L,S}(+-,00)$
2. $\mathbf{a}_{L,S}(+-\gamma)$
3. $\mathbf{a}_{L,S}(\pi\, l\, \nu)$
4. $\mathbf{a}_{L,S}(\pi\, \pi\, \pi)$

- **Results**
- **Conclusions**

The unitarity relation and CPT

QFT + Lorentz Invariance + Locality $\Rightarrow$ CPT invariance

Violation from QG $\propto$ $(E/M_{planck})^n$ $\begin{cases} n=1,2,\ldots \\ M_{planck} \equiv G_N^{-1/2} \sim 10^{19}\ \text{GeV} \end{cases}$

$$K^0 - \overline{K}^0$$

$$i\frac{d}{dt}\begin{bmatrix} K \\ \overline{K} \end{bmatrix} = [M - i\Gamma/2]\begin{bmatrix} K \\ \overline{K} \end{bmatrix}$$

CPT invariance $\Rightarrow$ $M_{11}=M_{22}$ $\Gamma_{11}=\Gamma_{22}$

$$|M_K - M_{\overline{K}}| < 10^{-18}\ GeV$$

If n=1 CPT-violating terms exist ... very close to M_K/M_{Planck}

The unitarity relation and CPT

The eigenstates:

$$|K_S\rangle = N_S\left[\,|+\rangle + \varepsilon_S|-\rangle\,\right]$$
$$|K_L\rangle = N_L\left[\,|-\rangle + \varepsilon_L|+\rangle\,\right]$$

$$\varepsilon_{S,L} \equiv \varepsilon \pm \delta$$

where:

$$\delta = \frac{i\left(M_K - M_{\overline{K}}\right) + \frac{1}{2}\left(\Gamma_K - \Gamma_{\overline{K}}\right)}{\Delta\Gamma}\cos\phi_{SW}\, e^{i\phi_{SW}}$$

$$\begin{cases} \Delta\Gamma \equiv \Gamma_S - \Gamma_L \\ \Delta M \equiv M_L - M_S \\ \tan(\phi_{SW}) \equiv 2\Delta M/\Delta\Gamma \end{cases}$$

$$\frac{1}{M_K}\begin{pmatrix} M_K - M_{\overline{K}} \\ 1/2\left(\Gamma_K - \Gamma_{\overline{K}}\right)\end{pmatrix} = \frac{\Delta\Gamma}{M_K\cos\phi_{SW}}\begin{pmatrix}\cos\phi_{SW} & -\sin\phi_{SW} \\ \sin\phi_{SW} & \cos\phi_{SW}\end{pmatrix}\begin{pmatrix}\Im(\delta) \\ \Re(\delta)\end{pmatrix} \approx O\left(10^{-14}\right)\begin{pmatrix}\Im(\delta) \\ \Re(\delta)\end{pmatrix}$$

If $\Gamma_K - \Gamma_{\overline{K}} = 0 \;\Rightarrow\; \frac{M_K - M_{\overline{K}}}{M_K} \approx 3\times10^{-14}\,\Im(\delta)$

The unitarity relation and CPT

$$\Re(\delta) \Rightarrow \begin{cases} A_{CPT} = \dfrac{P(\overline{\mathrm{K}} \to \overline{\mathrm{K}}(t)) - P(\mathrm{K} \to \mathrm{K}(t))}{P(\overline{\mathrm{K}} \to \overline{\mathrm{K}}(t)) + P(\mathrm{K} \to \mathrm{K}(t))} = 4\,\Re(\delta) \\ A_S - A_L = 4\,\Re(\delta) + O(\Delta S \neq \Delta Q) \end{cases}$$

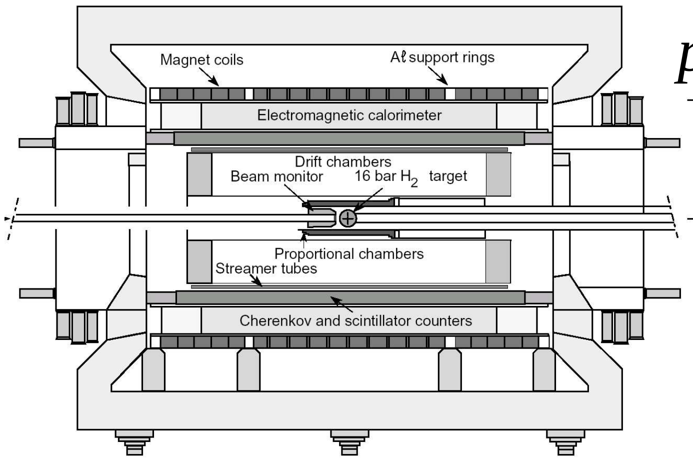
$A_{S,L}$ charge asymmetry in $\mathrm{K}_{S,L}$ semileptonic decay

Unitarity relation

$$\Im(\delta) \Rightarrow \left[\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right] \frac{\Re(\varepsilon) - i\Im(\delta)}{1 + |\varepsilon|^2} = \frac{1}{\Gamma_S - \Gamma_L} \sum_f a_S^*(f) a_L(f)$$

$a_{S,L}(f)$ $\mathrm{K}_{S,L}$ decay amplitudes

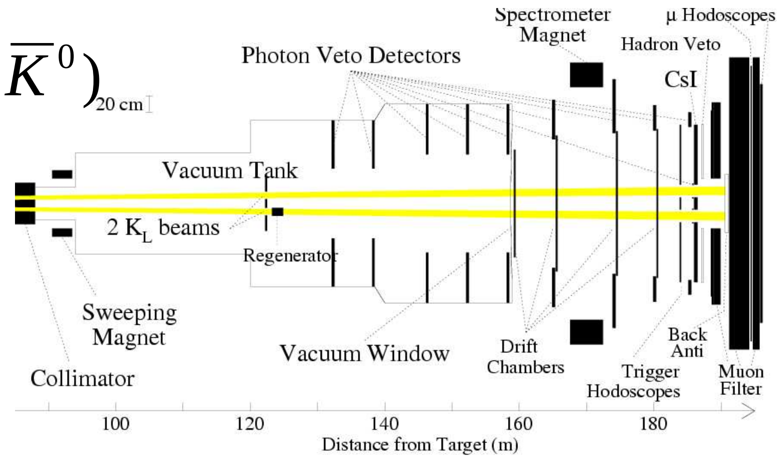
Experiments

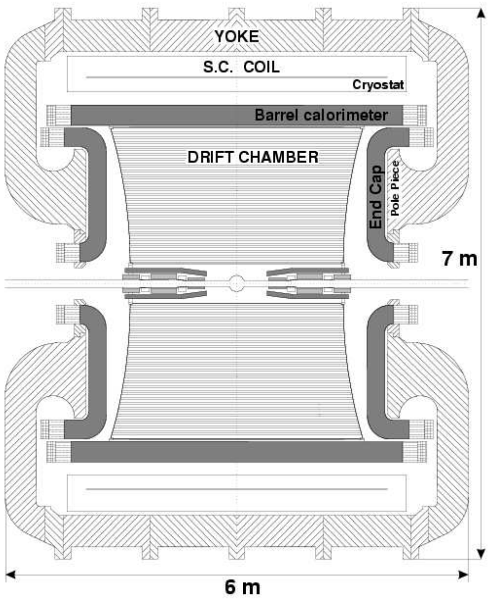


CPLEAR

$p\bar{p} \rightarrow K^{\pm}\pi^{\mp}K^{0}(\bar{K}^{0})$

P_K~500 MeV





KLOE

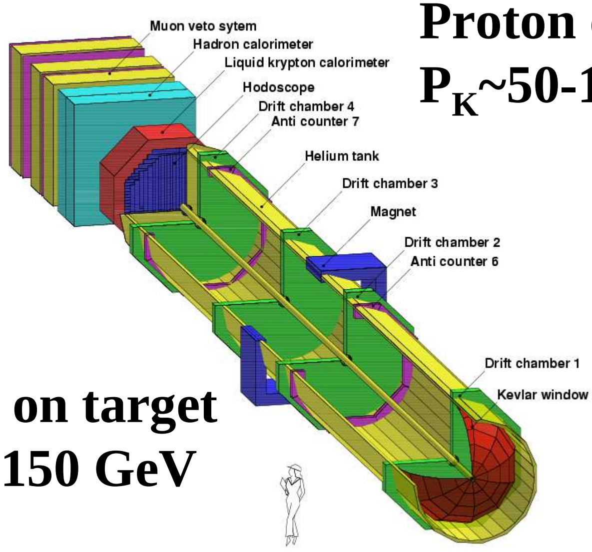
$\varphi \rightarrow K_S K_L$

P_K~110 MeV

KTeV

Proton on target

P_K~50-150 GeV



NA48

Proton on target

P_K~50-150 GeV

Experimental inputs to *Re(δ)*

CPLEAR fit of time dependent asymmetry A_δ with semileptonic decays

$$\frac{\overline{N}^+(t)-N^-(t)}{\overline{N}^+(t)+N^-(t)}+\frac{\overline{N}^-(t)-N^+(t)}{\overline{N}^-(t)+N^+(t)}=f(\Re(\delta),\Im(\delta),\Re(x_-),\Im(x_+))$$

Result improved adding as a constraint: **ΔS≠ΔQ**

$$A_S-A_L=4[\Re(\delta)+\Re(x_-)]$$

$$\Re(\delta)=(3.0\pm3.3\pm0.6)\times10^{-4}$$
$$\Im(\delta)=(-1.5\pm2.3\pm0.3)\times10^{-2}$$
$$\Re(x_-)=(0.2\pm1.3\pm0.3)\times10^{-2}$$
$$\Im(x_+)=(1.2\pm2.2\pm0.3)\times10^{-2}$$

$$\Rightarrow$$

$$\Re(\delta)=(3.3\pm2.8)\times10^{-4}$$
$$\Im(\delta)=(-1.1\pm0.7)\times10^{-2}$$
$$\Re(x_-)=(-0.03\pm0.25)\times10^{-2}$$
$$\Im(x_+)=(0.8\pm0.7)\times10^{-2}$$

All correlations are taken into account

Experimental inputs to *Im(δ)*

$\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^-\gamma_{DE}$

$$\alpha_f = \frac{1}{\Gamma_S} a_S^*(f) a_L(f) = \eta_f BR(K_S \to f)$$

Inputs for all BR's, ϕ^{+-}, and ϕ^{00}

$\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$

$$\alpha_f = \frac{1}{\Gamma_S} a_S^*(f) a_L(f) = \frac{\tau_S}{\tau_L} \eta_f^* BR(K_L \to f)$$

Inputs for η_{+-0}, K_L BR's, and U.L. on $BR(K_S \to 3\pi^0)$

output

$\pi l \nu$

$$\alpha_{kl3} = 2\frac{\tau_S}{\tau_L} BR(K_L \to \pi l \nu)\left[\Re(\varepsilon) - \Re(y) + i\Im(\delta) + i\Im(x_+)\right]$$

Inputs for all BR's and asymmetries

$A_\delta \oplus A_S - A_L$

¼$(A_S + A_L)$

y ~~CPT~~ in decays

Other decays < 10^{-6}

Inputs also for τ_S , τ_L , and ϕ_{SW}

$K_S \to \pi^+\pi^- / K_S \to \pi^0\pi^0$

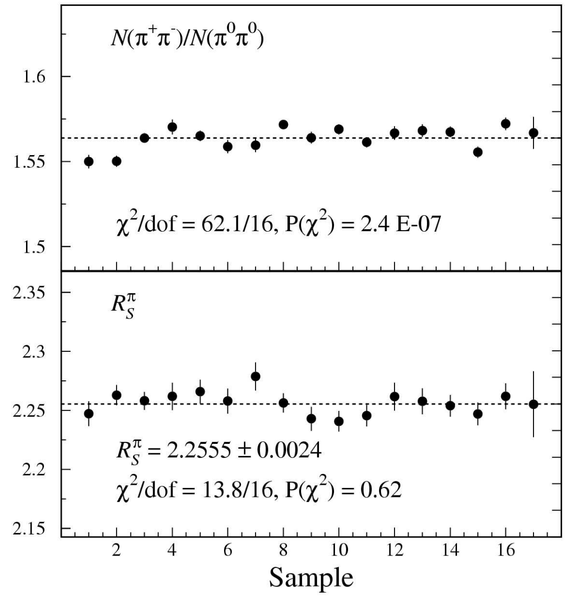
KLOE

Over 400×10^6 $\varphi \to K_S K_L$

Pure K_S beam

$$\frac{\Gamma(K_S \to \pi^+\pi^-(\gamma))}{\Gamma(K_S \to \pi^0\pi^0)} = (2.2549 \pm 0.0054)$$

hep-ex/0601025 Submitted EPJC



Combined with KLOE $K_S \to \pi e \nu$ to get single BR's

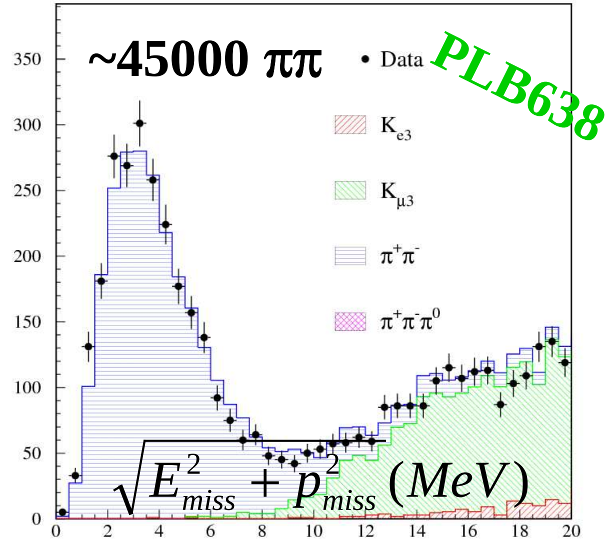
$K_L \to \pi^+\pi^-(\gamma_{IB})$

KLOE measures the ratio $BR(K_L \to \pi\pi)/(K_L \to \pi\mu\nu)$

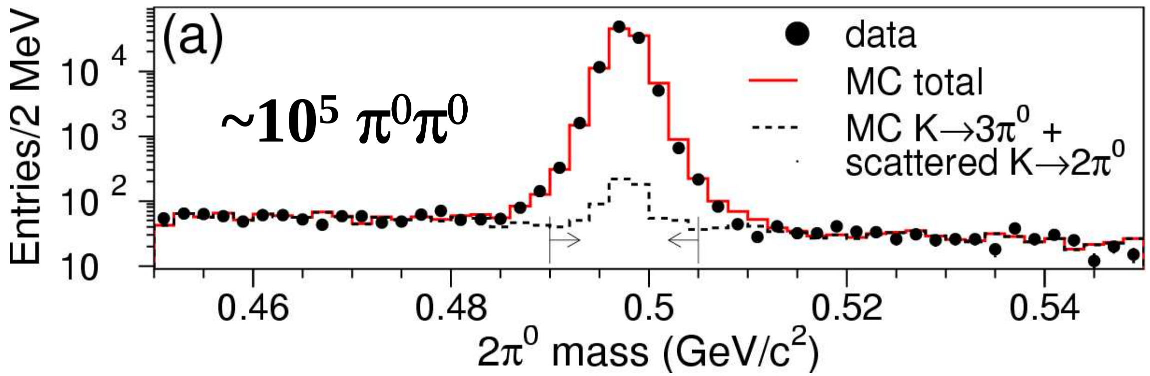
Event counting from fit to: $\sqrt{E_{miss}^2 + p_{miss}^2}$

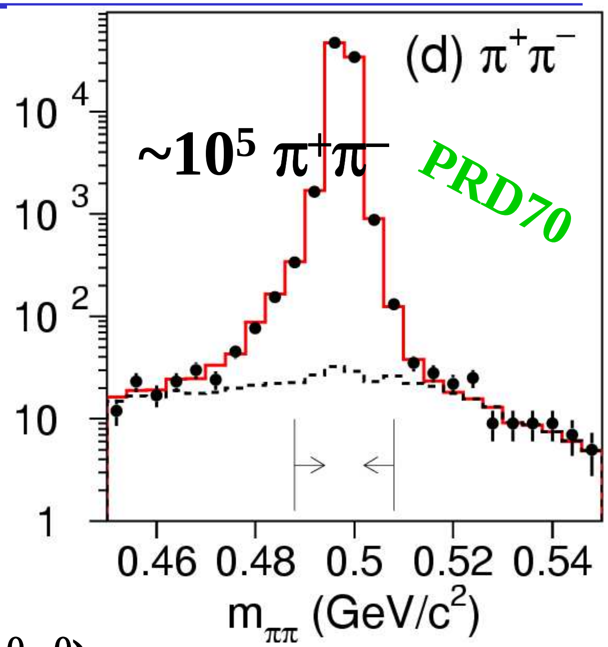
Combining with $K_L \to \pi\mu\nu$ BR from KLOE

$$\Gamma\left(K_L \to \pi^+\pi^-(\gamma^{IB+DE})\right) = (1.963 \pm 0.021) \times 10^{-3}$$



$K_L \rightarrow \pi^+\pi^-(\gamma_{IB}), \pi^0\pi^0$





KTeV

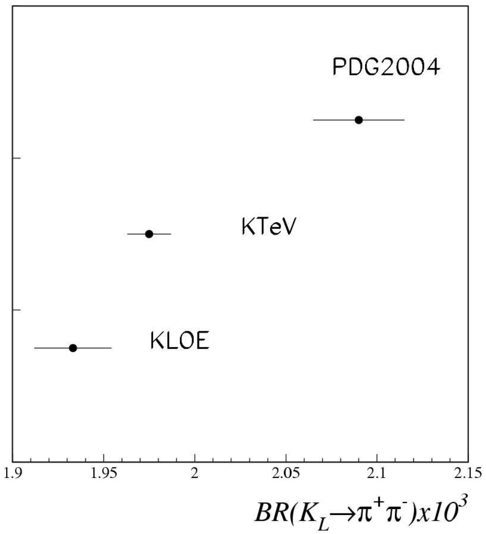
Measures: $\Gamma(K_L \rightarrow \pi\pi\pi, \pi\mu\nu, \pi\pi)/\Gamma(Ke3)$, $\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\pi^0)$

$$BR\left(K_L \rightarrow \pi^+\pi^-(\gamma)\right) = (1.975 \pm 0.012) \times 10^{-3}$$

$$BR\left(K_L \rightarrow \pi^0\pi^0\right) = (0.865 \pm 0.010) \times 10^{-3}$$

$$\alpha(\pi^+\pi^-) \times 10^3 = (1.126 \pm 0.014) + i(1.064 \pm 0.014)$$

$$\alpha(\pi^0\pi^0) \times 10^3 = (0.494 \pm 0.007) + i(0.472 \pm 0.008)$$



$K_L \to \pi^+\pi^-\gamma_{DE}$

KTeV

Sample 10^5 $\pi\pi\gamma$ with E_γ>20 MeV

Contribution from:

Electric amplitude $\propto (p_1 \bullet \varepsilon - p_2 \bullet \varepsilon)$

Magnetic amplitude $\propto (\varepsilon^{ijkl} p_1 p_2 q \varepsilon)$

$$\frac{d\Gamma}{dE_\gamma} \propto \left(\left| E_{BR} + E_{direct} \right|^2 + \left| M_{direct} \right|^2 \right)$$

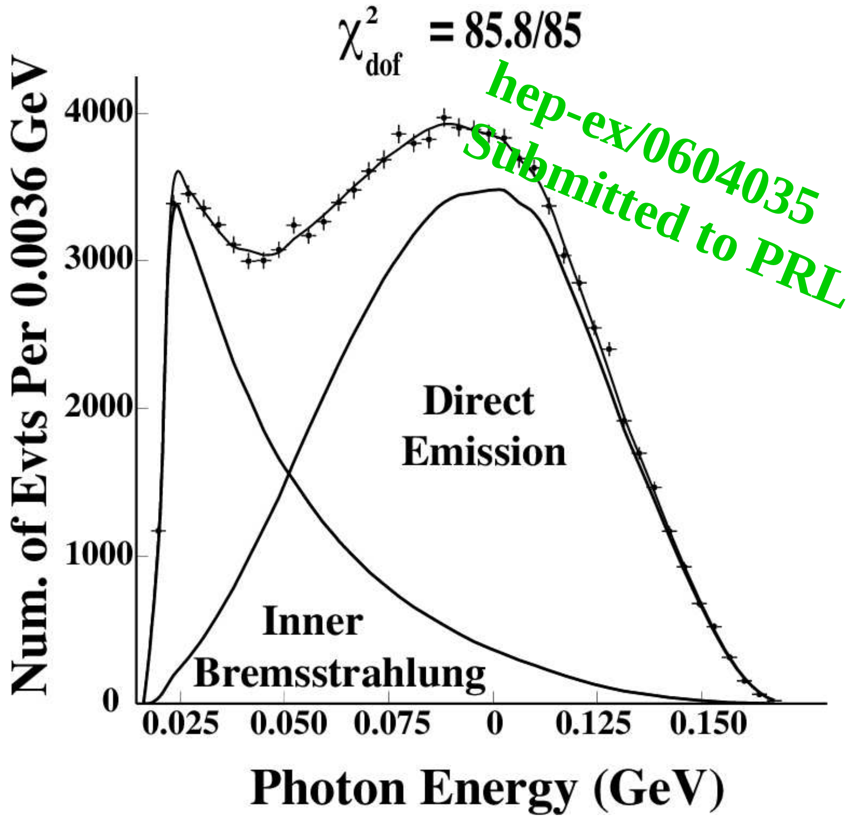
No inteference between E and M when summing over photon helicity

$$\left| g_{E1} \right| \le 0.21\,(90\%CL)$$

$$\left| \tilde{g}_{M1} \right| = (1.198 \pm 0.093)$$

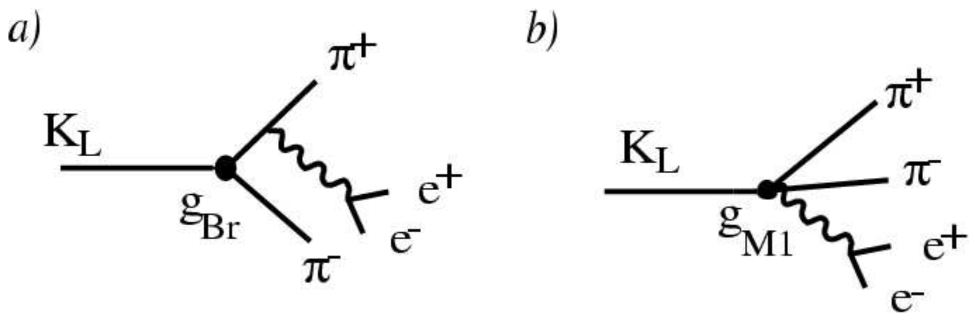
$$a_1 / a_2 = (-0.738 \pm 0.019)\,GeV^2$$

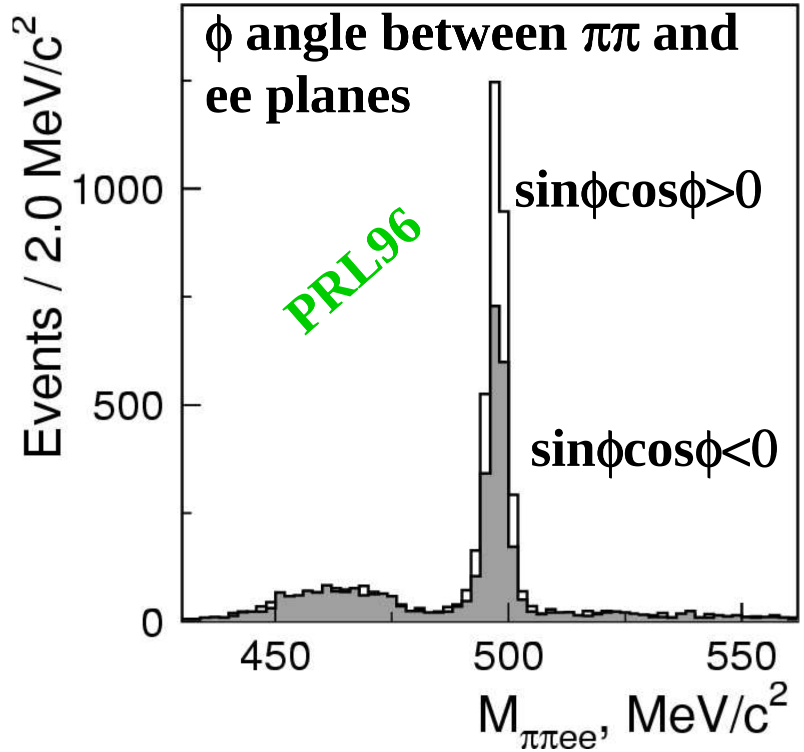
Combining with U.L. for K_S DE (E731)



$$\alpha(\pi^+\pi^-\gamma_{DE}) \times 10^3 = (0.000 \pm 0.002) + i(0.000 \pm 0.002)$$

$K_L \rightarrow \pi^+\pi^- e^+ e^-$





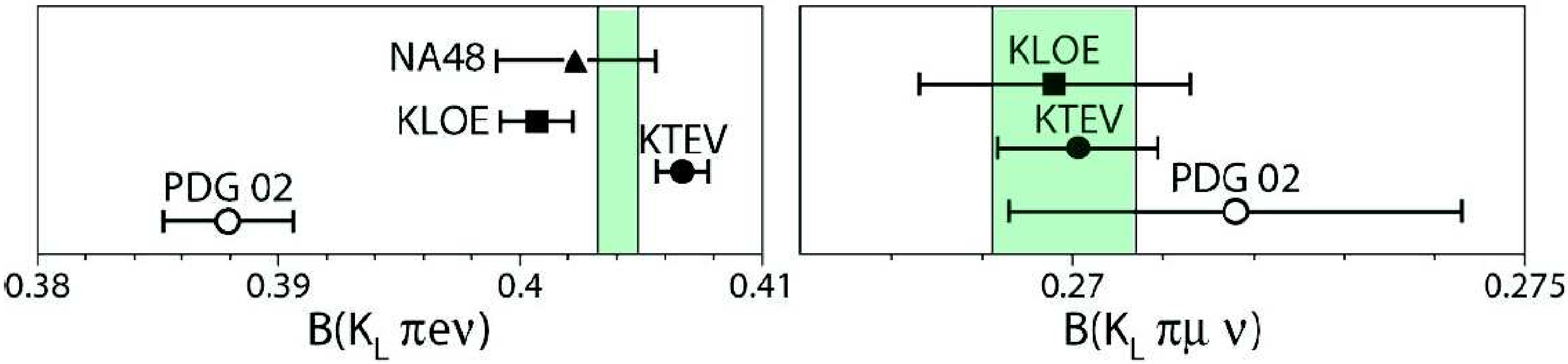
Different way of measuring DE
Measure CP violating interference M⊗E
KTeV with a sample of ~5000 ππee events
BR(K_L)~10^{-7}

$$\left|\tilde{g}_{M1}\right| = (1.11 \pm 0.14)$$

$$a_1 / a_2 = (-0.744 \pm 0.042)\ GeV^2$$

Previous measurement from NA48 (EPJC30) with ~1000 K_L
(also measured K_S decay)

$K_L \rightarrow \pi l \nu$



New measurements from KLOE, KTeV and NA48

KLOE BR(Ke3), BR(Kμ3) ⇐ **we use this for $\alpha(\pi l \nu)$**

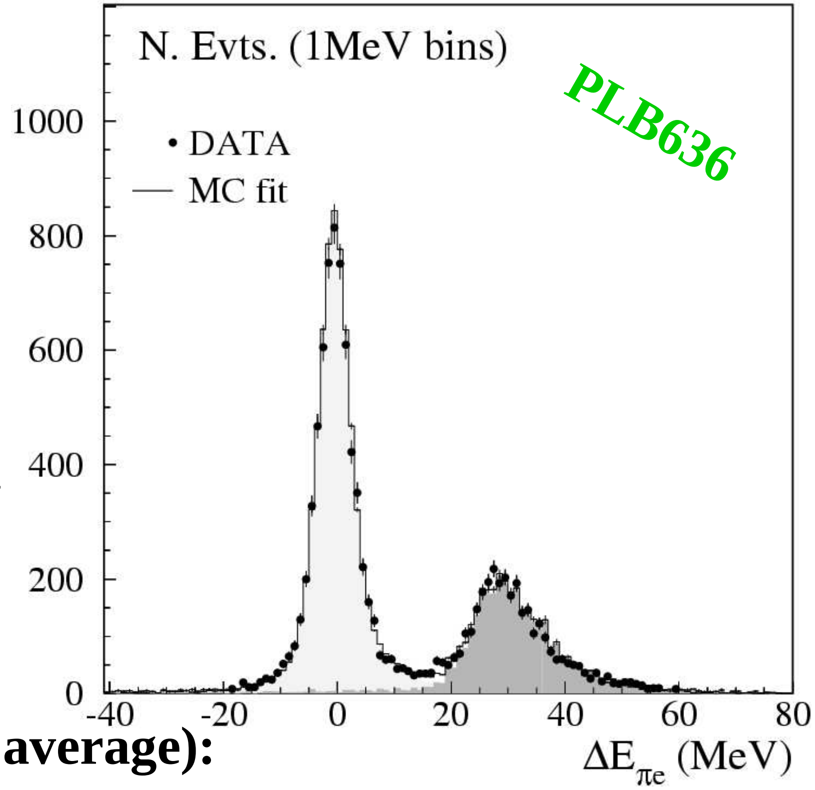
KTeV BR(Ke3), BR(Kμ3)

NA48 BR(Ke3)

See Antonelli's talk

$K_S \to \pi e \nu$

KLOE
Measures the ratio $\Gamma(\pi e \nu)/\Gamma(\pi^+\pi^-)$ for each charge mode and A_S
Sample of 6500 events per charge
Event counting: fit to E_{miss}-P_{miss} ($\Delta E \pi e$) and other kinematical variables



$$BR(K_S \to \pi e \nu) = (7.028 \pm 0.092) \times 10^{-4}$$

$$A_S = (1.5 \pm 10.0) \times 10^{-3}$$

Combining with A_L=(3.34±0.06)×10^{-3} (PDG average):

$$A_S - A_L = 4[\Re(\delta) + \Re(x_-)] = (-1.8 \pm 10.0) \times 10^{-3}$$

$$A_S + A_L = 4[\Re(\varepsilon) - \Re(y)] = (-4.8 \pm 10.0) \times 10^{-3}$$

$$\alpha(\pi l \nu)_{\Im(\delta)=0} \times 10^3 = (0.003 \pm 0.002) + i(-0.019 \pm 0.017)$$

$K_S \rightarrow \pi\mu\nu$

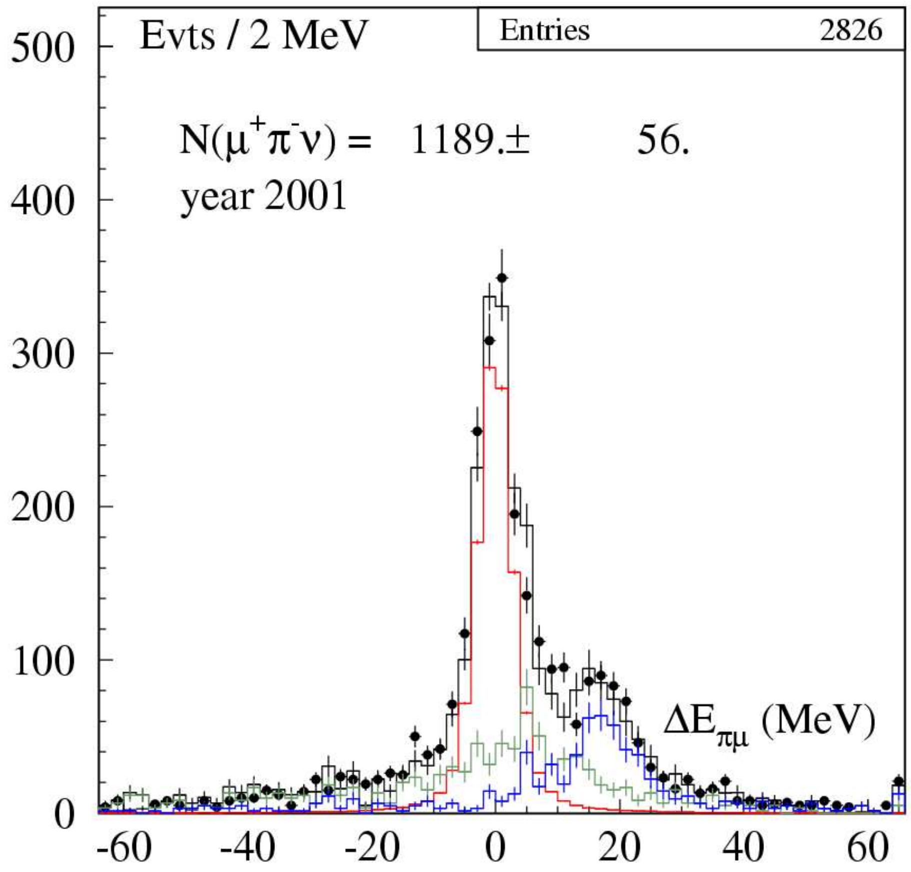
Semileptonic modes (PDG2005)		
$\pi^{\pm} e^{\mp} \nu_e$	[c]	$(6.9 \pm 0.4) \times 10^{-4}$
$\pi^{\pm} \mu^{\mp} \nu_\mu$	[c]	

KLOE

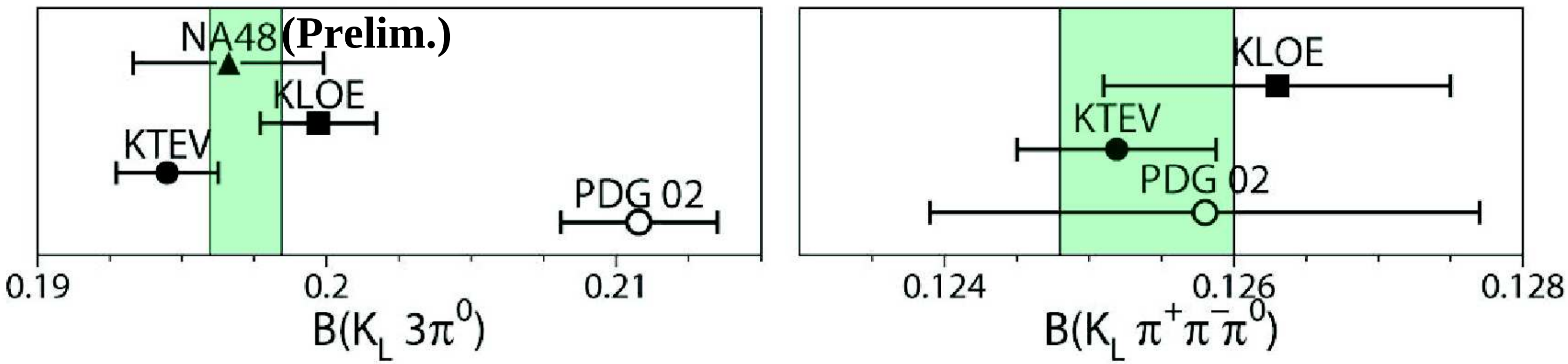
Never measured before, BR~5×10^{-4}.
Event counting with fit to E_{miss}-P_{miss} ($\Delta E\pi\mu$) distribution.

Selected ~3500 events per charge with ~400 pb^{-1}.

Statistical error:
$\delta BR/BR$~3% per charge mode
$\delta A\mu$~0.01



$K_L \rightarrow \pi\pi\pi$



New measurements from KLOE, KTeV and NA48

KLOE BR($\pi^+\pi^-\pi^0$), BR($3\pi^0$) $\Leftarrow$ **we use this for $\alpha(\pi\pi\pi)$**

KTeV BR($\pi^+\pi^-\pi^0$), BR($3\pi^0$)

NA48 BR($3\pi^0$)

See Antonelli's talk

$K_S \to \pi^+\pi^-\pi^0$

$$\begin{cases} a_L = a_L^{CP-}(X,Y) \\ a_S = a_S^{CP+}(X,Y) + a_S^{CP-}(X,Y) \\ a^{CP\pm}(X,Y) = \mp a^{CP\pm}(-X,Y) \end{cases}$$

$$\lambda = \frac{\int_{X>0} dXdY a_L^* a_S^{CP+}}{\int_{X>0} dXdY |a_L|^2}$$

$$\eta_{+-0} = \frac{\int dXdY a_L^* a_S^{CP-}}{\int dXdY |a_L|^2} \Rightarrow \alpha(\pi^+\pi^-\pi^0)$$

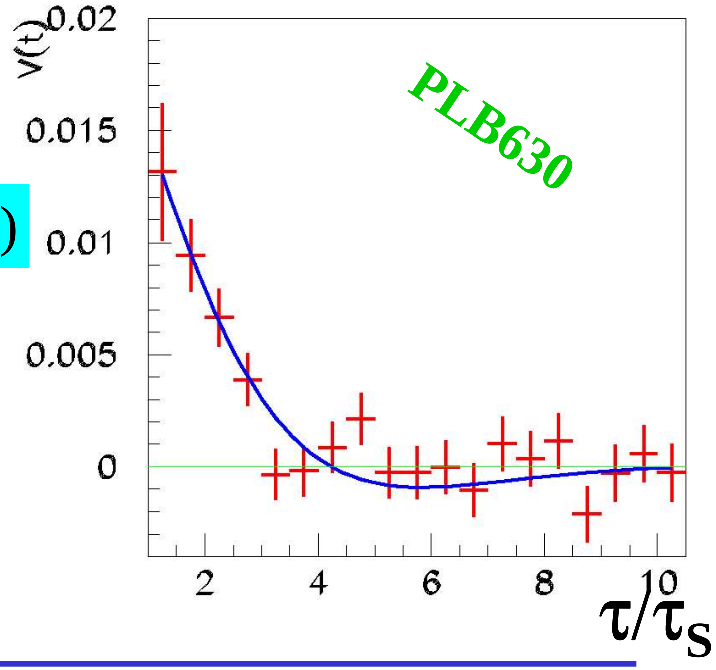
CPLEAR $\frac{\overline{N}_{3\pi}(t) - N_{3\pi}(t)}{\overline{N}_{3\pi}(t) + N_{3\pi}(t)}$

$$\eta_{+-0} \times 10^3 = (-2 \pm 7) + i(-2 \pm 9)$$

$$\alpha(\pi^+\pi^-\pi^0) \times 10^3 = (0.001 \pm 0.002) + i(-0.001 \pm 0.002)$$

NA48 $\frac{N_{3\pi}^{X>0} - N_{3\pi}^{X<0}}{N_{3\pi}^{X>0} + N_{3\pi}^{X<0}}$

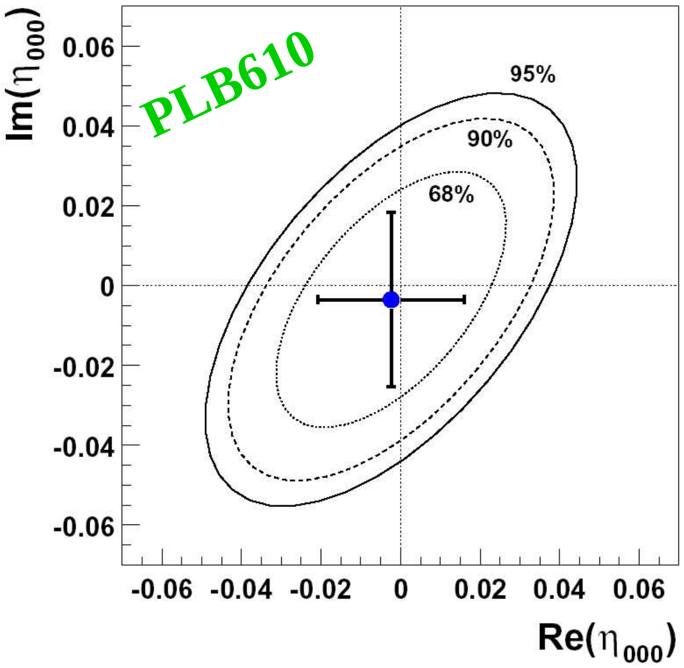
$$\lambda = (0.038 \pm 0.010) + i(-0.013 \pm 0.007)$$



$K_S \rightarrow \pi^0\pi^0\pi^0$

CP violating decay BR~10^{-9}
Before NA48 and KLOE measurements, $\Im(\delta)$ was limited by the poor knowledge of η_{000}

Two different ways for measuring η_{000}



NA48

Measures $K \rightarrow 3\pi^0$ rate as a function of proper time, with 5×10^6 $K_{S,L} \rightarrow 3\pi^0$ from 'near target', normalized to the rate of 10^8 $K_L \rightarrow 3\pi^0$ from 'far target'

$$f_{3\pi^0}(t) \propto 1 + |\eta_{000}|^2 e^{-(\Gamma_S - \Gamma_L)t}$$

$$+ 2D(p)\left[\Re(\eta_{000})\cos(\Delta m t) - \Im(\eta_{000})\sin(\Delta m t)\right] e^{-\frac{1}{2}(\Gamma_S - \Gamma_L)t}$$

$$\eta_{000} = (-0.002 \pm 0.019) + i(-0.003 \pm 0.021)$$

$K_S \to \pi^0\pi^0\pi^0$

KLOE

Direct search for K_S decays

~5×10^8 K_S-K_L

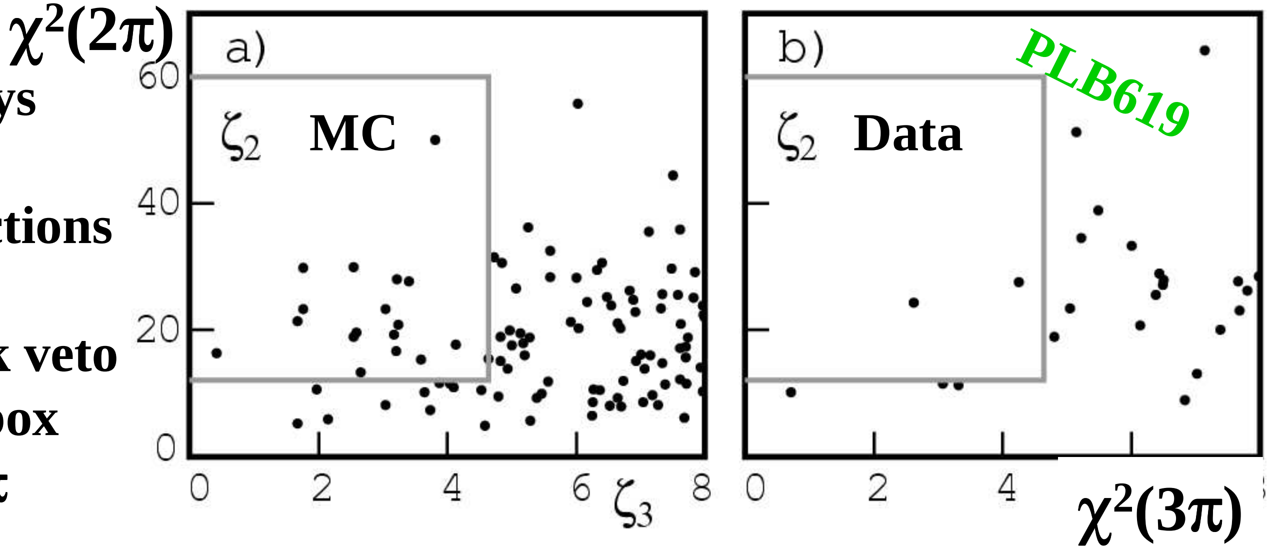
K_S tagged with K_L interactions in EmC

Selection: 6 clusters, track veto

Event counting in signal box defined by χ^2 in 2π and 3π hypothesis

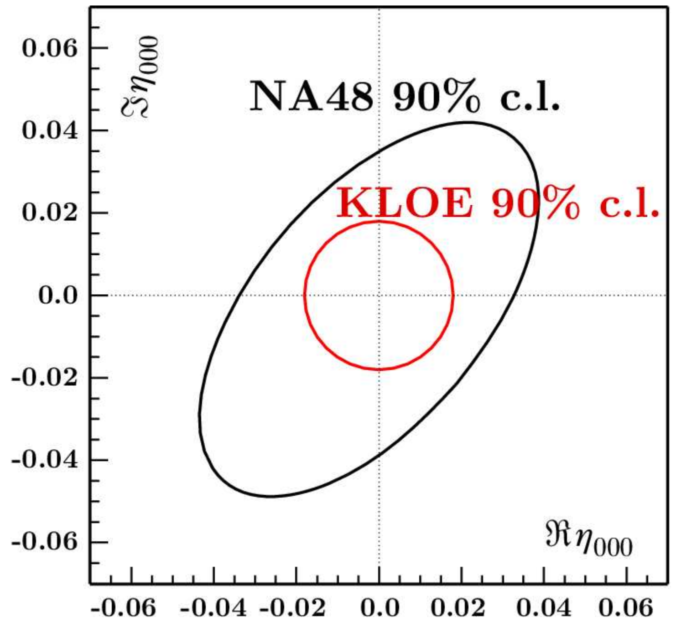
Normalized to $K_S\to2\pi^0$ events

2 events found, 3 bkg events expected

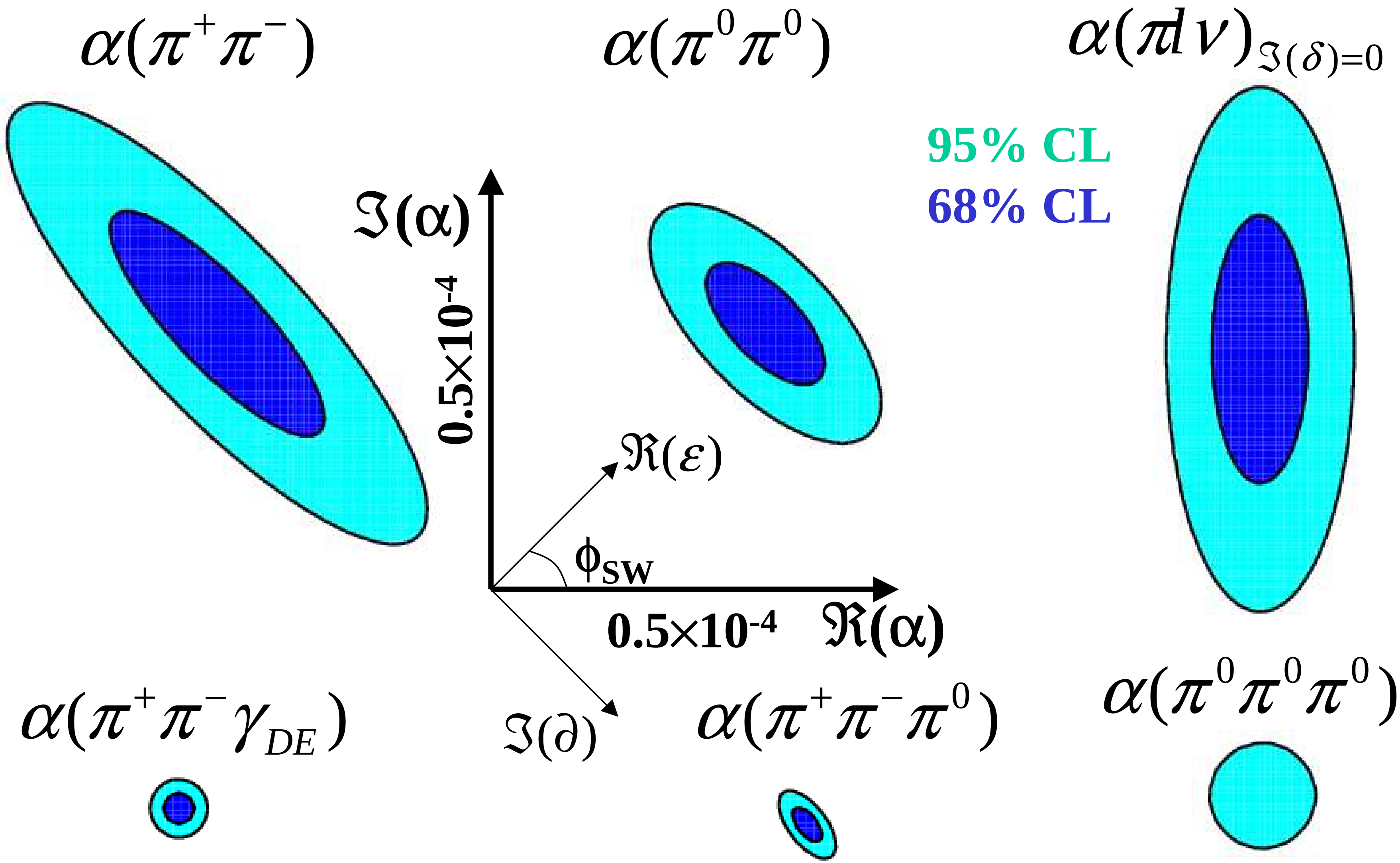


$$90\%\ C.L.\begin{cases} BR(K_S \to 3\pi^0) \le 1.2\times10^{-7} \\ |\eta_{000}| \le 0.018 \end{cases}$$

$$|\alpha(\pi^0\pi^0\pi^0)|\times10^3 =< 0.010\ \ 95\%\ C.L.$$

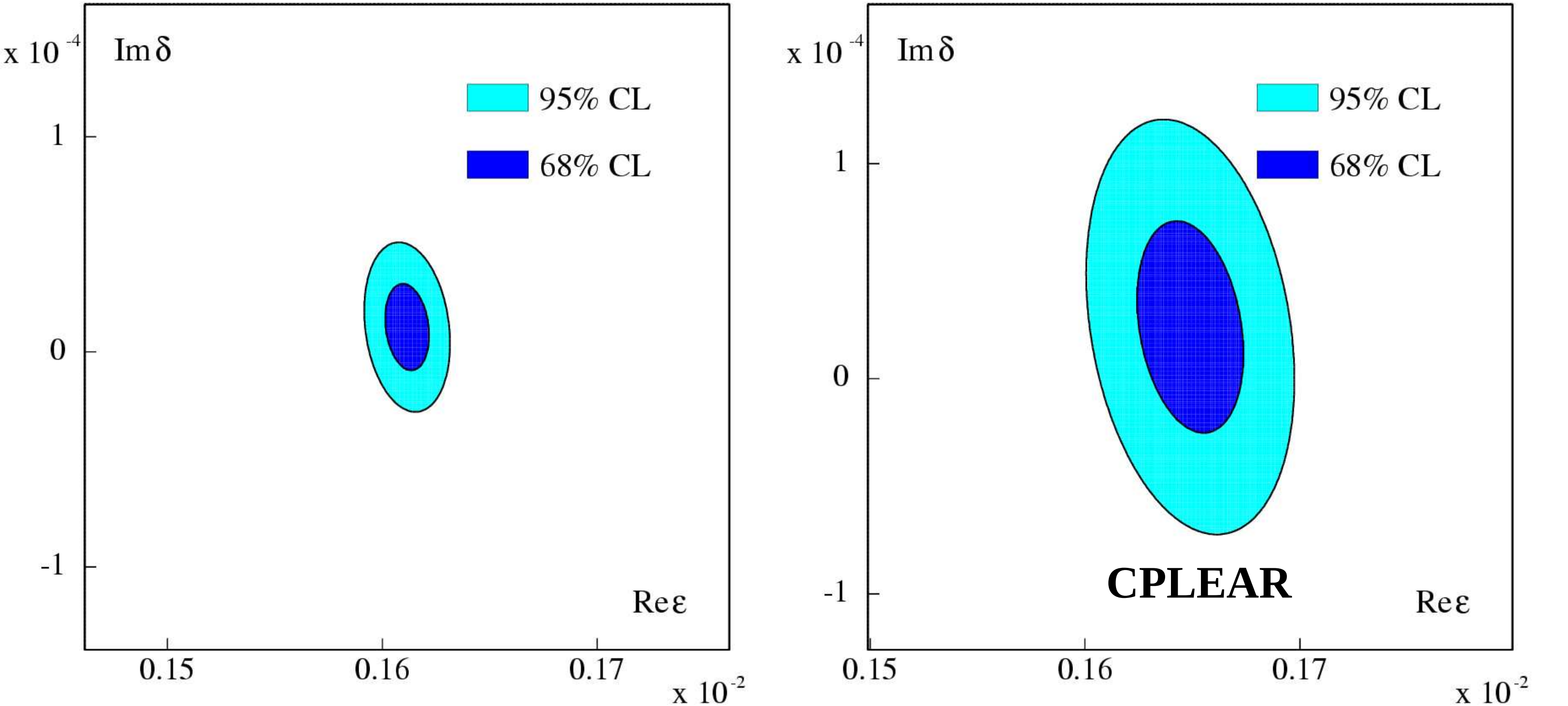


Results



$\alpha(\pi^+\pi^-)$
$\alpha(\pi^0\pi^0)$
$\alpha(\pi l \nu)_{\Im(\delta)=0}$
95% CL
68% CL
$\Im(\alpha)$
0.5×10^{-4}
$\Re(\varepsilon)$
ϕ_{SW}
0.5×10^{-4}
$\Re(\alpha)$
$\alpha(\pi^+\pi^-\gamma_{DE})$
$\Im(\partial)$
$\alpha(\pi^+\pi^-\pi^0)$
$\alpha(\pi^0\pi^0\pi^0)$

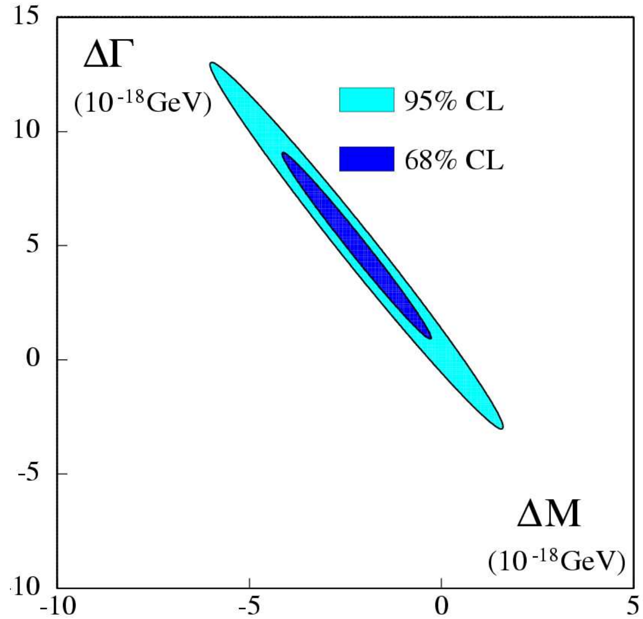
Results

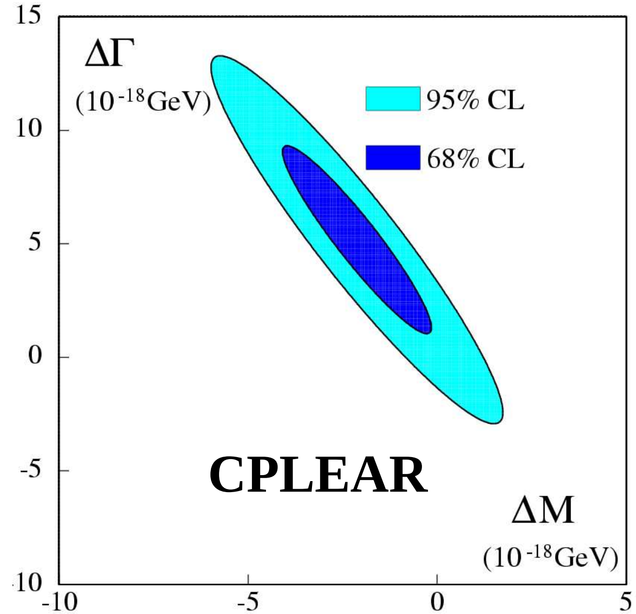


$$\Re(\varepsilon) = (161.0 \pm 1.0) \times 10^{-5}$$
$$\Im(\delta) = (1.3 \pm 2.0) \times 10^{-5}$$

$$\Re(\varepsilon) = (164.9 \pm 2.5) \times 10^{-5}$$
$$\Im(\delta) = (2.4 \pm 5.0) \times 10^{-5}$$

Results





$$\Gamma_K - \Gamma_{\overline{K}} = (5 \pm 4) \times 10^{-18} GeV$$

$$M_K - M_{\overline{K}} = (-2.2 \pm 2.0) \times 10^{-18} GeV$$

$$\Gamma_K - \Gamma_{\overline{K}} = (3.9 \pm 4.2) \times 10^{-18} GeV$$

$$M_K - M_{\overline{K}} = (-1.5 \pm 2.0) \times 10^{-18} GeV$$

$$\Gamma_K - \Gamma_{\overline{K}} = 0$$

$$-4 \times 10^{-19} < M_K - M_{\overline{K}} < 7 \times 10^{-19}\ GeV \quad 95\% CL$$

$$-10 \times 10^{-19} < M_K - M_{\overline{K}} < 17 \times 10^{-19}\ GeV \quad 95\% CL$$

Conclusions

The unitarity relation allows us to test CPT symmetry close to the scale M_K/M_{planck}.
We have done a new determination of the CP and CPT parameters combining the results from CPT asymmetries of CPLEAR with the unitatiry relation.
We obtain an accuracy improvement of ~2.5 for both $\Re(\varepsilon)$ and $\Im(\delta)$. The improvement is due both to the measurement of η_{000} and A_S.
The limiting quantities are now:
- **$\Im(x_+)$ and ϕ_{+-} for $\Im(\delta)$**
- **η_{+-} and η_{00} for $\Re(\varepsilon)$**

KLOE has analyzed only 1/5 of its data sample (2.5 fb^{-1}). The full sample should allow us to further reduce the uncertainty on these fundamental parameters.